# Triplet fermion signatures at the $e^-e^+$ collider using fat jet

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***Abstract*** The addition of SU(2)$_L$ triplet fermions of zero hypercharge with the Standard Model (SM) helps to explain the origin of the neutrino mass by the so-called seesaw mechanism. Such a scenario is commonly know as the type-III seesaw model. After the electroweak symmetry breaking the mixings between the light and heavy mass eigenstates of the neutral leptons are developed which play important roles in the study of the charged and neutral multiplets of the triplet fermions at the colliders. In this poster we study such interactions to produce these multiplets of the triplet fermion at the $e^-e^+$ collider. We focus on the heavy triplets, for example, having mass in the TeV scale so that their decay products including the SM the gauge bosons can be sufficiently boosted, leading to a fat jet. Hence we probe the mixing between light-heavy mass eigenstates of the neutrinos and compare the results with the bounds obtained by the electroweak precision study. We discuss about the possibility of obtaining displaced vertices of the triplet fermion in the collider using general parameters in the Dirac Yukawa coupling.

## A. Introduction

Neutrino oscillation data and the existence of the tiny neutrino mass is a source of the beyond the SM physics. Hence SM needs to be expanded. In this poster we extend the SM with an $SU(2)_L$ triplet fermion with zero hypercharge which is commonly known as the type-III seesaw mechanism through the light heavy mixings. Such triplet fermions have neutral and charged multiplets which can be produced at the $e^-e^+$ collider. We can probe the light heavy mixing at the $e^-e^+$ collider.

## B. Type-III Seesaw mechanism

The interactions of the triplets can be written as

$$\mathcal{L}_{\rm int} = \mathcal{L}_{\rm SM} + {\rm Tr}(\bar{\tilde{\Sigma}} i\gamma^\mu D_\mu \tilde{\Sigma}) - \frac{1}{2}M_\Sigma {\rm Tr}(\bar{\tilde{\Sigma}}\tilde{\Sigma}^c + \bar{\tilde{\Sigma}}^c\tilde{\Sigma}) - \sqrt{2}(\bar{\ell_L} Y^\dagger \tilde{\Sigma} H + H^\dagger \bar{\tilde{\Sigma}} Y \ell_L) \quad (1)$$

Hence through the light-heavy mixing and the electroweak symmetry breaking the partial decay widths of the neutral multiplet ($\Sigma^0$) of the triplet fermion as

$$\Gamma(\Sigma^0 \to \ell^+ W) = \Gamma(\Sigma^0 \to \ell^- W) = \frac{g^2|V_\ell|^2}{64\pi}\Big(\frac{M_\Sigma^3}{M_W^2}\Big)\Big(1-\frac{M_W^2}{M_\Sigma^2}\Big)^2\Big(1+2\frac{M_W^2}{M_\Sigma^2}\Big)$$
$$\Gamma(\Sigma^0 \to \nu Z) = \frac{g^2|V_\ell|^2}{64\pi\cos^2\theta_W}\Big(\frac{M_\Sigma^3}{M_Z^2}\Big)\Big(1-\frac{M_Z^2}{M_\Sigma^2}\Big)^2\Big(1+2\frac{M_Z^2}{M_\Sigma^2}\Big)$$
$$\Gamma(\Sigma^0 \to \nu h) = \frac{g^2|V_\ell|^2}{64\pi}\Big(\frac{M_\Sigma^3}{M_W^2}\Big)\Big(1-\frac{M_h^2}{M_\Sigma^2}\Big)^2 \quad (2)$$

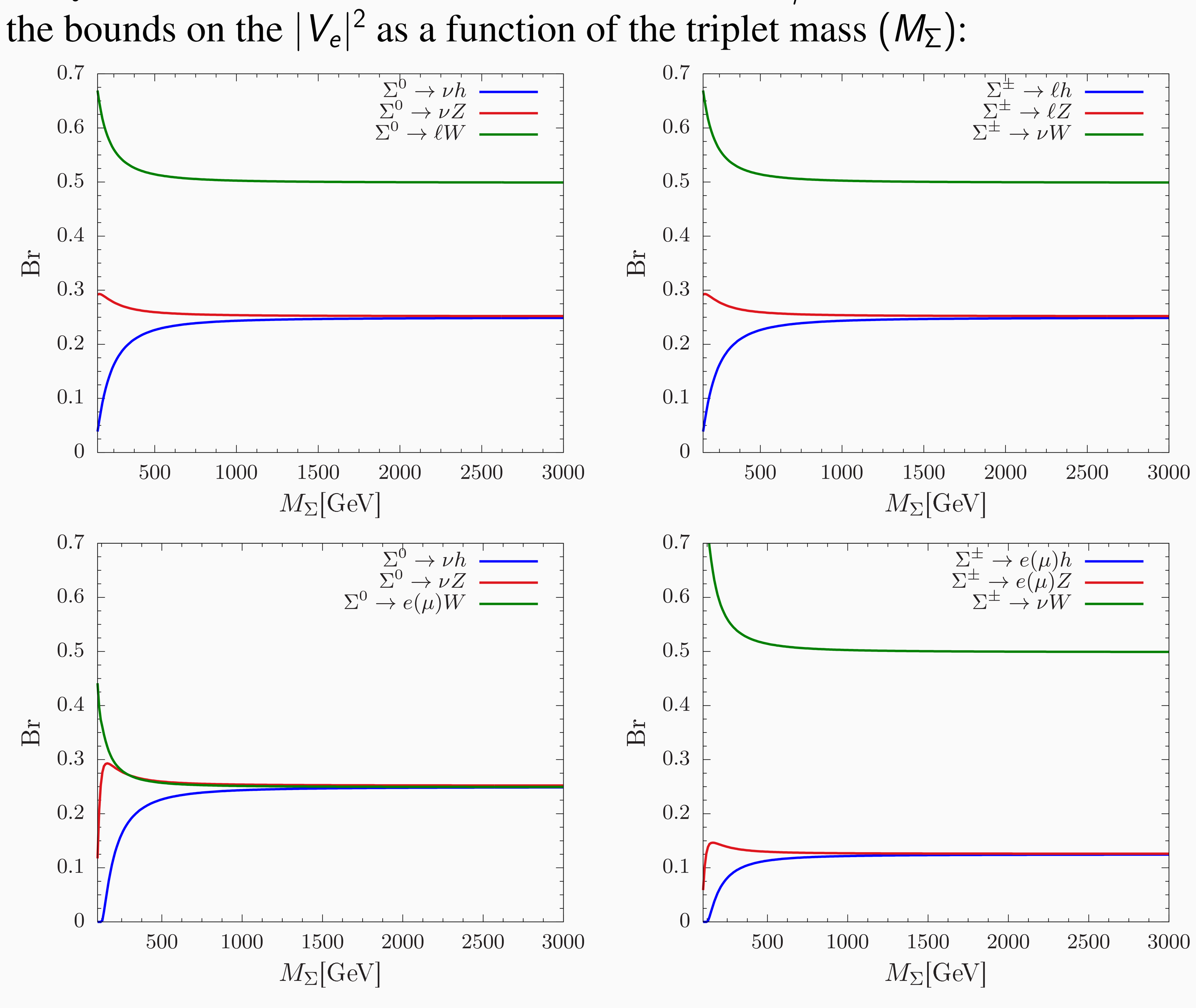
for the Majorana neutrinos and the partial decay widths of the charged multiplet ($\Sigma^\pm$) of the triplet fermion as

$$\Gamma(\Sigma^\pm \to \nu W) = \frac{g^2|V_\ell|^2}{32\pi}\Big(\frac{M_\Sigma^3}{M_W^2}\Big)\Big(1-\frac{M_W^2}{M_\Sigma^2}\Big)^2\Big(1+2\frac{M_W^2}{M_\Sigma^2}\Big)$$
$$\Gamma(\Sigma^\pm \to \ell Z) = \frac{g^2|V_\ell|^2}{64\pi\cos^2\theta_W}\Big(\frac{M_\Sigma^3}{M_Z^2}\Big)\Big(1-\frac{M_Z^2}{M_\Sigma^2}\Big)^2\Big(1+2\frac{M_Z^2}{M_\Sigma^2}\Big)$$
$$\Gamma(\Sigma^\pm \to \ell h) = \frac{g^2|V_\ell|^2}{64\pi}\Big(\frac{M_\Sigma^3}{M_W^2}\Big)\Big(1-\frac{M_h^2}{M_\Sigma^2}\Big)^2, \quad (3)$$

respectively. $M_W$, $M_Z$ and $M_h$ are the $W$, $Z$ and Higgs boson masses respectively in SM. If the mass splitting ($\Delta M$) between the charged ($\Sigma^\pm$) and neutral ($\Sigma^0$) multiplets induced by the SM gauge bosons is of the order of the pion mass [**?**], $\Sigma^\pm$ can show the following additional decay modes

$$\Gamma(\Sigma^\pm \to \Sigma^0\pi^\pm) = \frac{2G_F^2 V_{ud}^2 \Delta M^3 f_\pi^2}{\pi}\sqrt{1-\frac{m_\pi^2}{\Delta M^2}}$$
$$\Gamma(\Sigma^\pm \to \Sigma^0 e\nu_e) = \frac{2G_F^2\Delta M^5}{15\pi}$$
$$\Gamma(\Sigma^\pm \to \Sigma^0\mu\nu_\mu) = 0.12\Gamma(\Sigma^\pm \to \Sigma^0 e\nu_e) \quad (4)$$

The value of the Fermi Constant, $G_F$ is $1.1663787\times10^{-5}$ GeV$^{-2}$, the CKM matrix element $V_{ud}$ is $0.97420\pm0.00021$ and the $\pi$ meson decay constant, $f_\pi$, can be taken as 0.13 GeV. The Branching ratios (Br) of $\Sigma^0$ and $\Sigma^\pm$ into the SM particles are shown in left panel and right panel of the following figure as a function of $M_\Sigma$ for $V_e = 0.019$, $V_\mu = 0$ and $V_\tau = 0$. The Branching ratios (Br) of $\Sigma^0$ and $\Sigma^\pm$ into the SM particles are shown in left panel and right panel of the following figure as a function of $M_\Sigma$ for $V_e = V_\mu = 0.016$ and $V_\tau = 0$. In this paper for the further analyses we consider the case with $V_e = 0.019$, $V_\mu = 0$ and $V_\tau = 0$ to estimate the bounds on the $|V_e|^2$ as a function of the triplet mass ($M_\Sigma$):

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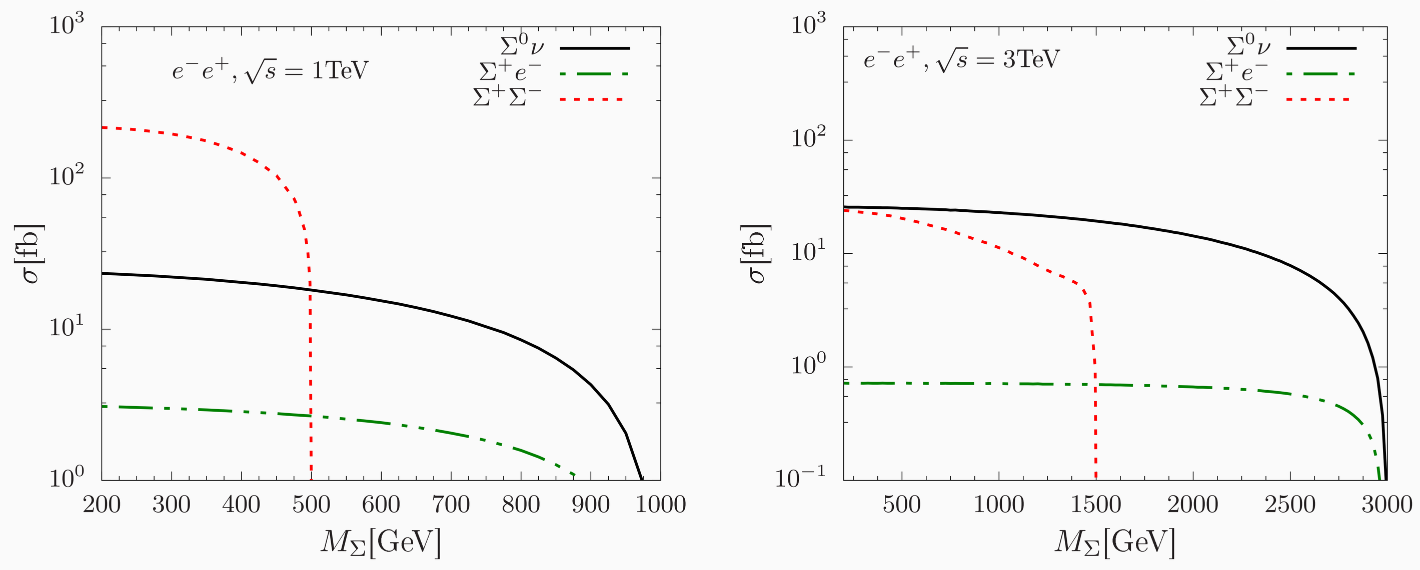
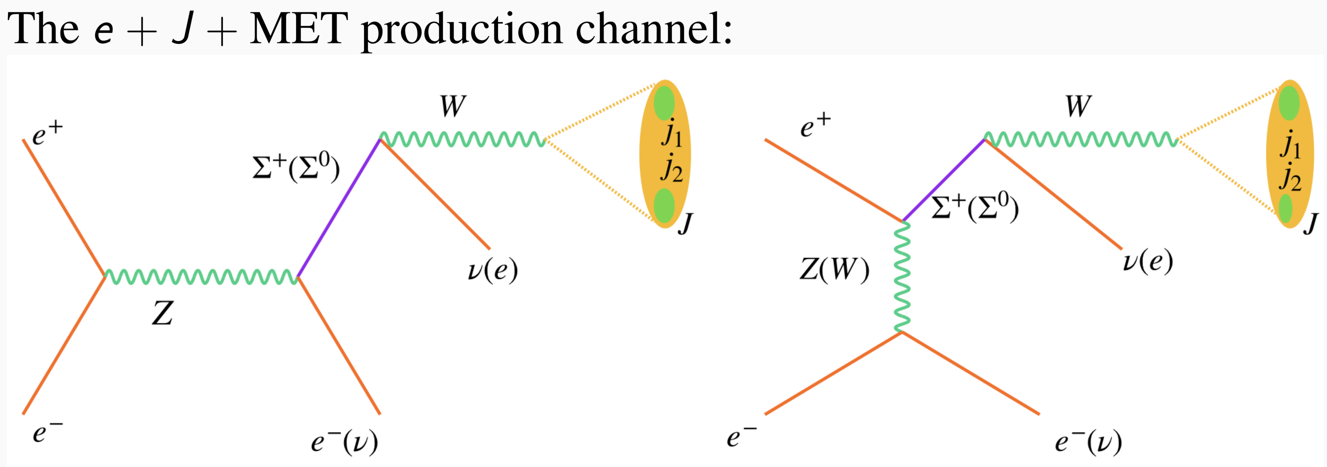
## C. Triplet production at the $e^-e^+$ collider (2005.02267)

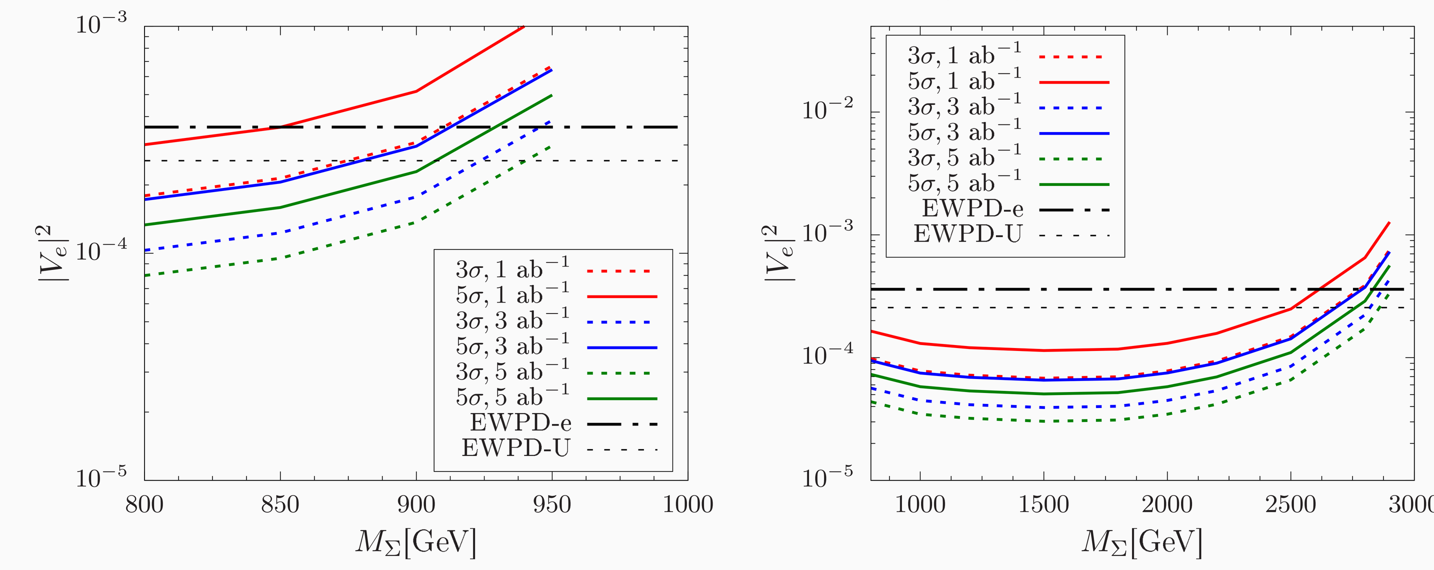
There are several production modes of the different multiplets of the triplet fermion. The triplet production cross section in the $e^-e^+$ collider with 1 TeV (left panel ) and 3 TeV (right panel) CM energies of the following figure as a function of the triplet mass ($M_\Sigma$):




The $e + J +$ MET production channel:




Criteria for the final event selection: (1) electrons in the final state should have the following transverse momentum ($p_T^e$) and pseudo-rapidity ($|\eta^e|$): $p_T^e > 10$ GeV, $|\eta^e| < 2.5$ (for $ep$ collider, $|\eta^e| < 5$), (2) jets are ordered in $p_T$ and they should have $p_T^j > 10$ GeV and $|\eta^j| < 2.5$, (3) leptons should be separated by $\Delta R_{\ell\ell} > 0.2$. (4) the jets and leptons should be separated by $\Delta R_{\ell j} > 0.3$, (5) fat Jet is constructed with radius parameter $R = 0.8$, (6) polar angle of the lepton and the fat jet $|\cos\theta_e| < 0.9$, (7) transverse momentum for the fat jet $p_T^J > 300$ GeV, (8) transverse momentum for the leading lepton $p_T^{e^\pm} > 300$ GeV, (9) fat jet mass $m_J > 70$ GeV. Applying the above criteria we find the bounds on the mixing $e^-e^+$ collider angle in the 1 TeV(left panel) and 3 TeV (right panel) of the following figure as a function of the triplet mass ($M_\Sigma$):

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## D. Displaced vertex (2006.04123)

The Dirac mass term between triplet, SM lepton after the EWSB can be generalized using a $3\times3$ orthogonal matrix $O$ as $M_D^{\rm NH/IH} = V_{\rm PMNS}^*\sqrt{D_{\rm NH/IH}}O\sqrt{M}$ where $O$ can have three choices like : (1) $O = 1_{3\times3}$, (2) $O$ = Real orthogonal matrix and (3) $O$ = Complex orthogonal matrix. Fitting the neutrino oscillation data (1811.05487) and comparing the results with constraints obtained from the electroweak precision, lepton flavor violating and non-unitarity (0509008, 0707.4058), we calculate the proper decay length for the triplet fermions at $M_\Sigma = 1$ TeV as

$$\mathrm{L}^{\Sigma_i^{0\rm NH/IH}} = \frac{1.97\times10^{-13}}{\Gamma^{\rm NH/IH}_{\Sigma_i^0}[\rm GeV]}[\rm mm], \ \ \text{and} \ \ \mathrm{L}^{\Sigma_i^{\pm\rm NH/IH}} = \frac{1.97\times10^{-13}}{\Gamma^{\rm NH/IH}_{\Sigma_i^\pm}[\rm GeV]}[\rm mm] \quad (5)$$

where $\Gamma$ is the total decay width which involves the mixing and hence $O$ gets involved in the proper decay length. In this case we consider three generations of the triplets. Due to this the lightest light neutrino mass eigenvalue will be a free parameter for the NH and IH cases and will be constrained by the PLANCK data, $\Sigma_i m_i \leq 0.12$ eV (1807.06209).We find that depending upon the lightest light neutrino mass the maximum decay length can reach up to 1 mm, 171 mm and $1.74\times10^6$ mm for the lightest light neutrino mass at $10^{-4}$ eV, $10^{-6}$ eV and $10^{-10}$ eV respectively.

## E. Conclusion

We have employed the fat-jet search strategy to find the bounds on the mass-mixing planes of the triplet involved in the neutrino mass generation mechanism comparing the bounds obtained from the electroweak precision test. We have found that the technique of the fat-jet search from the boosted object van be very useful and the bounds can be measured between 3-5 $\Sigma$ significance below the constraints obtained from the EWPD. We have also found that generalized Dirac Yukawa coupling can lead us to study the displaced vertex signature in the high energy colliders.